VERIFICATION OF TRANSLATION

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Title of the Invention: LIGHT DIFFRACTION METHOD AND DIFFRACTION DEVICE, DIFFRACTION GRATING USED FOR THEM, AND POSITION ENCODING DEVICE

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am the translator of the document attached and I state that the following is a true translation to the best of my knowledge and belief of Japanese Patent Application No. 2003-270002 (filing date: July 1, 2003).

At Osaka, Japan

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[Document Name] Claims

[Claim 1]

A diffraction grating comprising:

a first layer having first light scatterers periodically arrayed, and

a second layer having second light scatterers arrayed with the same period as that of the first light scatterers of the first layer, wherein:

a direction in which incident light applied from a direction out of planes of the first layer and the second layer is diffracted by these layers is aligned with a direction in which a unit formed of one of the first light scatterers and one of the second light scatterers, which are adjacent to each other, scatters the incident light especially intensely so that diffracted light with a single order or a plurality of orders is enhanced selectively.

[Claim 2]

The diffraction grating according to claim 1, wherein the first light scatterers and the second light scatterers are spheres and are two-dimensionally arrayed in each of the layers respectively.

[Claim 3]

The diffraction grating according to claim 2, wherein the spheres have equal refractive indices and diameters.

[Claim 4]

The diffraction grating according to claim 1, wherein the first light scatterers and the second light scatterers are cylinders and are one-dimensionally arrayed in each of the layers respectively.

[Claim 5]

The diffraction grating according to claim 4, wherein the cylinders have equal refractive indices and diameters.

[Claim 6]

The diffraction grating according to claim 1, wherein the first light scatterers and the second light scatterers are lenses in an almost axially symmetrical shape and are two-dimensionally arrayed in each of the layers respectively.

[Claim 7]

The diffraction grating according to claim 1, wherein the first light scatterers and the second light scatterers are lenses in an almost plane symmetrical shape and are one-dimensionally arrayed in each of the layers respectively.

[Claim 8]

The diffraction grating according to claim 6 or 7, wherein the lenses have

equal focal distances.

[Claim 9]

The diffraction grating according to claim 1, wherein the period with which the light scatterers are arrayed in each of the layers is in a range of 1/2 times to 100 times with respect to a wavelength of incident light in the medium surrounding the diffraction grating.

[Claim 10]

The diffraction grating according to claim 1, wherein the first layer and the second layer are in close contact with each other.

[Claim 11]

The diffraction grating according to claim 1, wherein the first layer and the second layer are monolayers and are disposed facing each other so that the surfaces of the light scatterers of each layer are in close vicinity to each other.

[Claim 12]

The diffraction grating according to claim 1, wherein a relative distance or in-plane positional relationship between the first layer and the second layer is changed by a driving device.

[Claim 13]

A diffraction device comprising:

the diffraction grating described in claim 2, 4, 6 or 7, and

a prism element whose two opposed faces are not parallel, wherein:

the diffraction grating described in claim 2, 4, 6 or 7 is combined with the prism element.

[Claim 14]

An optical waveguide device comprising:

the diffraction grating described in claim 2, 4, 6, or 7, and

an optical waveguide, wherein:

the diffraction grating described in claim 2, 4, 6, or 7 is combined with the optical waveguide.

[Claim 15]

A position encoding device for detecting, based on interrelation of an intensity of a single diffracted light or intensities of a plurality of diffracted lights, in-plane relative positions of two structure bodies that move relatively, wherein the first layer of the diffraction grating described in claim 2, 4, 6, or 7 is fixed to one of the two structure bodies and the second layer described in

claim 2, 4, 6, or 7 is fixed to the other structure body.

[Document Name] Description

[Title of the Invention] DIFFRACTION GRATING AND DEVICE USING THE SAME

[Field of the Invention]

[0001]

The present invention relates to a diffraction grating to be used for spectrum measurement of electromagnetic waves mainly in the optical wavelength range, signal and image measurements involving selecting of a predetermined wavelength, or for changing and branching of the propagating direction of electromagnetic waves. The present invention also relates to a device using the diffraction grating.

[Background Art]

[0002]

A diffraction grating is generally a one-dimensional periodic array of linear protrusions having a triangular or rectangular cross-sectional shape. Depending on the purposes, a two-dimensional periodic array of protrusions or recesses in a pyramidal or rectangular parallelepiped shape also is used. Diffraction gratings are classified roughly into two types, a reflective type and a transmission type depending on the style of use.

[0003]

Fig. 15 is a schematic view of a conventional blazed diffraction grating.

[0004]

In this figure, reference numeral 1 denotes a main body of a diffraction grating, reference numeral 2 denotes a surface layer, reference numeral 3 denotes incident light, reference numeral 4 denotes reflected light, reference numeral 5 denotes reflected diffraction light, reference numeral 6 denotes refracted light and reference numeral 7 denotes transmitting diffraction light.

[0005]

When the period of the diffraction grating is greater than half the

wavelength of incident light, generally a plurality of diffracted lights 5 and 7 are produced both on the reflection side and the transmission side. The angles of these diffracted lights 5 and 7 are determined by the wavelength, incident direction and the period of the incident light 3, so even the incident lights that are incident from the same direction can result in diffracted lights 5 and 7 in different directions depending on their wavelengths.

[0006]

This principle makes it possible to split white light into spectra and to detect only the intensity of a specified wavelength by a light detection device placed in a specified direction, and so forth. In a reflective diffraction grating, a metal film is coated on a surface thereof, and therefore, light cannot proceed through to the transmission side. In a transmission diffraction grating, a surface layer is omitted or it is subjected to an anti-reflection coating.

[0007]

Conventional diffraction gratings have employed the technology of processing its cross section in an appropriate sawtooth-like triangular shape to attain high diffraction efficiency. As illustrated in Fig. 15, the incident light 3 is divided into the reflected light 4 and the refracted light 6 at a slope of one triangle. In the case of a reflective diffraction grating, the inclination angle and the period of the slopes are determined so that the reflected diffraction light 5 with a wavelength that is required to be diffracted efficiently can proceed in the direction coinciding with that of the reflected light 4. In the case of a transmission diffraction grating, its design is conducted so that the direction of desired transmitting diffraction light 7 coincide with that of the refracted light 6.

[0008]

This optimization of the cross-sectional shape for obtaining high diffraction efficiency is called blazing, and a diffraction grating that is optimized in this way is called a blazed diffraction grating.

[0009]

Nonpatent Document 1 below summarizes historically important knowledge about conventional diffraction gratings.

[0010]

Patent Document 1 discloses an optical diffraction grating for selecting the wavelength of light and changing the propagating direction of light by using a resonant Bragg reflection phenomenon.

[0011]

Further, Patent Document 2 discloses a position matching device in which a physical optical element is formed on a face of a first object and that of a second object each in order to determine the relative position of the first object and the second object facing each other, the diffracted light occurring when light is incident on one of the physical optical elements is made incident on the other physical optical element, and the distribution of the quantity of light of the diffraction pattern given on a predetermined face by the other physical optical element is detected by a detecting device.

[Patent Document 1] JP2001-091717A

[Patent Documents 2] JP2513281B

[Nonpatent Document 1] D. Maystre(ed.), "Selected Papers on Diffraction Gratings" (SPIE, Washington, 1993)

[Nonpatent Document 2] "Kogaku Kobo - Shitte iruyode igaini shiranai kaisetsu koshi, tokuni kyomei ryoiki" Kogaku (diffraction grating that looks familiar but unexpectedly is unknown, especially in the resonance domain" optics), Vol. 29, No. 5, pp. 338 to 339 (2000)

[Nonpatent Document 3] H. T. Miyazaki, H. Miyazaki, and K. Miyano, "Anomalous scattering from dielectric bispheres in the specular direction", Optics Letters, Vol. 27, No.14, pp. 1208 to 1210 (2002)

[Nonpatent Document 4] S. H. Park and Y. Xia, "Assembly of Mesoscale Particles over Large Areas and Its Application in Fabricating Tunable Optical Filters", Langmuir, Vol. 15, pp. 266 to 273 (1999)

[Nonpatent Document 5] A. van Blaaderen, R. Ruel, and P. Wiltzius,

"Template-directed colloidal crystallization", Nature, Vol. 385, pp. 321 to 324 (1997)

[Disclosure of Invention]

[Problem to be solved by the Invention]

[0012]

The blazing principle discussed above, however, can be applied only to the diffraction grating with a period considerably greater than the wavelength because it utilizes geometrical optical phenomena such as reflection and refraction. This type of diffraction grating is called a diffraction grating in the scalar domain. The diffraction grating in the scalar domain may be satisfactory in the case of using a very high diffraction order or in the case where only a very small angle of diffraction is necessary; however, when a low order and a large angle of diffraction are desired, the period and wavelength should be designed to be close values so as to be different by several times at most.

[0013]

This type of diffraction grating is called a resonance domain diffraction grating. Unlike the diffraction gratings in the scalar domain, no clear design theory of blazing has been offered for such resonance domain diffraction gratings. For this reason, resonance domain diffraction gratings are designed by solving Maxwell's equations as rigorously as possible to search for a desirable cross-sectional shape. The above-mentioned Nonpatent Document 2 indicates problem about blazing of diffraction gratings in the resonance domain.

[0014]

Fabricating a blazed diffraction grating as designed has not yet been so easy to date, even for the one in the scalar domain with a large period. In every age, the best precision processing technology at the time has been employed for the fabrication of diffraction gratings, and consequently, diffraction gratings always have been expensive elements that can be

manufactured only by exclusive manufacturers. In earlier times, precision processing machines called ruling engines were used, and such equipment that can produce high-quality diffraction gratings was limited even in the world. Although many of them have been replaced with optical interference exposure techniques, highly sophisticated techniques such as special ion etching and precision replication are required for achieving accurate blaze shapes, and the manufacturers that have such techniques are still limited. The above-mentioned Nonpatent Document 1 describes details of such techniques.

[0015]

What has been especially inconvenient in using conventional diffraction gratings is the lack of flexibility of the blazing condition. Once the incident direction, diffraction direction, period, required wavelength, and required diffraction order are determined, the appropriate blazing shape can be determined easily. However, when a diffraction grating is used as an optical spectroscope in particular, the diffraction grating is, for example, rotated with respect to the incident light and it must be used even in a condition that falls outside the blazing condition. For this reason, in designing an optical spectroscope, there has been no other option but to limit its use to a specific wavelength as a typically used wavelength, so it has been only within a certain operational range around the specified wavelength for which high efficiency can be guaranteed.

[0016]

In view of the foregoing circumstances, it is an object of the present invention to provide a novel blazing principle that is simple and effective even in the resonance domain and to open up the way of realizing a high efficiency diffraction grating by a relatively simple fabrication method. Further, it is another object of the invention to provide a diffracting grating with tunability that can realize optimum blazing condition according to various use conditions by a control signal from outside, and to provide a device using the diffraction

grating.

[Means for Solving the Problem]

[0017]

In order to achieve the above-mentioned objects, the present invention provides:

[1] A diffraction grating including a first layer having first light scatterers periodically arrayed therein and a second layer having second light scatterers arrayed therein with the same period as that of the first light scatterers of the first layer. A direction in which incident light applied from a direction out of planes of the first layer and the second layer is diffracted by these layers is aligned with a direction in which a unit formed of one of the first light scatterers and one of the second light scatterers, which are adjacent to each other, scatters the incident light especially intensely so that diffracted light with a single order or a plurality of orders is enhanced selectively.

[0018]

[2] The diffraction grating according to [1] above, wherein the first light scatterers and the second light scatterers are spheres and are two-dimensionally arrayed in each of the layers respectively.

[0019]

[3] The diffraction grating according to [2] above, wherein the spheres have equal refractive indices and diameters.

[0020]

[4] The diffraction grating according to [1] above, wherein the first light scatterers and the second light scatterers are cylinders and are one-dimensionally arrayed in each of the layers respectively.

[0021]

[5] The diffraction grating according to [4] above, wherein the cylinders have equal refractive indices and diameters.

[0022]

[6] The diffraction grating according to [1] above, wherein the first

light scatterers and the second light scatterers are lenses in an almost axially symmetrical shape and are two-dimensionally arrayed in each of the layers respectively.

[0023]

[7] The diffraction grating according to [1] above, wherein the first light scatterers and the second light scatterers are lenses in an almost plane symmetrical shape and are one-dimensionally arrayed in each of the layers respectively.

[0024]

[8] The diffraction grating according to [6] or [7] above, wherein the lenses have equal focal distances.

[0025]

[9] The diffraction grating according to [1] above, wherein the period with which the light scatterers are arrayed in each of the layers is in a range of 1/2 times to 100 times with respect to a wavelength of incident light in the medium surrounding the diffraction grating.

[0026]

[10] The diffraction grating according to [1] above, wherein the first layer and the second layer are in close contact with each other.

[0027]

[11] The diffraction grating according to [1] above, wherein the first layer and the second layer are monolayers and are disposed facing each other so that the surfaces of the light scatterers of each layer are in close vicinity to each other.

[0028]

[12] The diffraction grating according to [1] above, wherein a relative distance or in-plane positional relationship between the first layer and the second layer is changed by a driving device.

[0029]

[13] A diffraction device including the diffraction grating described in

[2], [4], [6] or [7] above, and a prism element whose two opposed faces are not parallel, wherein the diffraction grating described in [2], [4], [6] or [7] is combined with the prism.

[0030]

[14] An optical waveguide device including the diffraction grating described in [2], [4], [6] or [7] above and an optical waveguide, wherein the diffraction grating described in [2], [4], [6] or [7] is combined with the optical waveguide.

[0031]

[15] A position encoding device for detecting, based on interrelation of an intensity of a single diffracted light or intensities of a plurality of diffracted lights, in-plane relative positions of two structure bodies that move relatively. The first layer of the diffraction grating described in [2], [4], [6] or [7] above is fixed to one of the two structure bodies and the second layer described in [2], [4], [6] or [7] above is fixed to the other structure body.

[0032]

As described above, the present invention utilizes specular-resonance-enhanced diffraction exhibited by a periodic structure formed of scattering units that exhibit specular resonance.

[0033]

First, the specular resonance is a scattering phenomenon in which when two transparent spheres having a relative refractive index of from 1.2 to 2.2 with respect to the surrounding medium are in close contact or in proximity with each other, a light beam obliquely incident on the axis connecting the centers of the two spheres undergoes intense specular reflection as if a mirror is placed at the position of the axis. The specular reflection occurs when two spheres have the same diameter. When two spheres have different diameters, light goes out in a specific direction determined by the ratio of the diameters and the incident direction (this case is also called specular resonance because the two phenomena are essentially

based on the same principle, although in this case the direction of reflection is not precisely the direction of specular reflection).

[0034]

The diameter range of the spheres that exhibit such a phenomenon is very wide; for visible light with a wavelength of from about 400 to about 700 nm, for example, specular resonance similarly can be observed with from microspheres having a diameter of about 1 μm to infinitely large spheres. This phenomenon can be approximately paraphrased as a light refraction phenomenon that occurs at the interface between two circular shapes and therefore also can be observed not only with spheres but also with cylinders that are in close contact or in proximity with one another with their axes being parallel. Here, in two spheres or two cylinders, the incident side functions as a focusing lens for focusing incident collimated light while the emission side functions as a collimating lens for restoring it to collimated light.

[0035]

Thus, specular resonance can be paraphrased in a broader sense as the phenomenon in which two appropriately disposed lenses cause a light beam obliquely incident on the axis connecting the centers of the two lenses to undergo intense specular reflection as if a mirror is placed at the axis. The above-mentioned Nonpatent Document 3 describes this phenomenon in detail based on experimental results and calculation results.

[0036]

Next, specular-resonance-enhanced diffraction is a phenomenon in which intense diffracted light is obtained in a structure body made of a periodic two-dimensional array of light scattering units that exhibit specular resonance, that is, light scattering units made of two spheres or two lenses, in the case where the direction of the diffracted light resulting from the periodic structure overlaps with the direction of the specular resonance light produced by each scattering unit. In cases where the scattering units are lenses that

are approximately in an axially symmetrical shape, such as in the case of spheres and spherical lenses, the two-dimensional structure body is formed by periodically arraying them two-dimensionally. In cases where the scattering units are lenses that are approximately in a plane symmetrical shape, such as in the case of cylinders and cylindrical lenses, the two-dimensional structure body is formed by periodically arraying them one-dimensionally.

[0037]

As for the specular-resonance-enhanced diffraction, the scattering phenomenon of specular resonance works as the blazing principle for diffraction gratings. The specular resonance phenomenon occurs with a sphere, cylinder and lens in a size slightly larger than the wavelength (specifically, a general guideline is a diameter that is 1.6 times or greater the wavelength), and is therefore an effective phenomenon also for diffraction gratings in the resonance domain with those being arrayed nearly in a close-packed configuration. The fact that spheres and microlenses that are small to a degree of resonance domain function similarly to macrolenses (in the scalar domain) had been unknown until the above-mentioned Nonpatent Document 3 was released.

[0038]

The simplest system that causes the specular resonance enhancement phenomenon is a bilayer close-packed structure of spheres or cylinders. Such a system can be realized by self-assembled aggregation of colloidal particles or cylinders, without requiring highly sophisticated process techniques. Moreover, the blazing condition is determined by the relative arrangement of two objects, not the fixed shapes in conventional blazed diffraction gratings; therefore, by changing the relative arrangement using a control signal from outside, tunability can be introduced to the blazing condition.

[Effects of the Invention]

[0039]

The present invention can realize a high efficiency blazed diffraction

grating even in the wavelength range commonly known as the resonance domain, based on a principle totally different from conventional principles. Conventional diffraction gratings have necessitated highly sophisticated precision processing technology and been costly; however, the diffraction gratings according to the present invention can be fabricated by a relatively simple fabrication method at low cost because they can be realized by self-assembly techniques of microspheres or cylinders.

[0040]

Moreover, in contrast to conventional diffraction gratings, which have a fixed blazing condition that has been set when designing them, the present invention makes it possible to tune the blazing condition by a control signal from outside so that optimum performance can be attained in various use conditions.

[0041]

Furthermore, by utilizing the present invention, low-cost or tunable optical spectroscopes, optical integrated circuits, and position detector devices can be realized.

[Best Mode for Carrying Out the Invention]

[0042]

The diffraction grating includes a first layer having first light scatterers periodically arrayed therein and a second layer having second light scatterers arrayed therein with the same period as that of the first light scatterers of the first layer. In a structure thus configured, a direction in which incident light applied from a direction out of planes of the first layer and the second layer is diffracted by these layers is aligned with a direction in which a unit formed of one of the first light scatterers and one of the second light scatterers, which are adjacent to each other, scatters the incident light especially intensely so that diffracted light with a single order or a plurality of orders is enhanced selectively. The diffraction grating can be fabricated by a relatively simple fabrication method at low cost. Moreover, it is possible to

tune the blazing condition by a control signal from outside so that optimum performance can be attained in various use conditions.

[0043]

The use of the diffraction grating makes it possible to obtain a diffraction device combined with a prism element whose two opposed faces are not parallel, an optical waveguide device combined with an optical waveguide, and a position encoding device for detecting the in-plane relative positions of two structure bodies.

[Example 1]

[0044]

Hereinafter, embodiments of the present invention will be described in detail.

[0045]

Fig. 1 is a view for describing specular-resonance-enhanced diffraction by a bilayer close-packed crystal of transparent microspheres according to the present invention. Fig. 1 (a) is a plan view in which the microspheres of the second layer thereof were partially removed, and Fig. 1 (b) is a front view of Fig. 1 (a).

[0046]

In this figure, reference numeral 10 denotes a diffraction grating, reference numeral 11 denotes a transparent substrate, and reference numeral 12 denotes transparent microspheres (light scatterers) of a first layer, reference numeral 13 denotes a close-packed crystal of the first layer formed of the microspheres 12, reference numeral 14 denotes transparent microspheres (light scatterers) of a second layer, and reference numeral 15 denotes a close-packed crystal of the second layer formed of the microspheres.

[0047]

In this way, the bilayer close-packed crystals 13 and 15 formed of transparent microspheres (light scatterers) 12 and 14 with a diameter of about 1 μm are formed on the transparent substrate 11. The materials for

the transparent microspheres (light scatterers) 12 and 14 are readily available as those made of polystyrene or silica with a uniform diameter are manufactured as spacer particles for liquid crystal displays and reagents for physical and chemical research.

[0048]

The bilayer close-packed crystals 13 and 15 can be fabricated easily without using special fabrication equipment. That is because particles that are uniform in their size and shape inherently tend to array themselves periodically in a self-assembled manner to crystallize. The above-mentioned Nonpatent Document 4 describes in detail a method for producing microsphere crystals with a large area having an arbitrary number of layers, and results of the production of different number of layers.

[0049]

The specular-resonance-enhanced diffraction on which the present invention is based is described in detail with reference to Fig. 1.

[0050]

The close-packed crystals 13 and 15 of each layer in this figure are triangular lattices. As shown in the plan view of Fig. 1 (a), it is assumed that the triangular lattice is formed so that each layer is parallel to the xy plane and one side of the triangular lattice is parallel to the y axis, and that the array of the second layer is obtained by shifting the array of the first layer in an x-axis direction and stacking it. At this time, as shown in the front cross-sectional view of Fig. 1 (b), bispheres are formed in parallel with the xz plane. The bispheres are inclined from the z axis by angle δ, and are arrayed along the x-axis direction with period p. In the array of Fig. 1, angle $\delta = 35.3°$.

[0051]

Assuming that the diameter of the spheres is D, the relationship that period $p = 0.866D$ will hold. As will be discussed later, the relationship of the inclination angle δ, the period p and the sphere diameter D changes depending on the configuration and arrangement of the crystal. When light

k_i with wavelength λ is incident from the direction normal to the transparent substrate 11 on the xz plane at an incident angle α, the direction θ that produces diffracted light k_o in the xz plane is given by the so-called grating equation $\sin\theta = \sin\alpha + m\lambda/p$, where m is an integer and a diffraction order.

[0052]

At this time, assuming the specular resonance in each bisphere also occurs simultaneously, $\theta = 2\delta - \alpha$ must also be satisfied simultaneously. From these, the condition in which specular-resonance-enhanced diffraction occurs can be expressed as $2\cos\delta\sin(\delta - \alpha) = m\lambda/p$. There are countless conditions that satisfy this relationship. Some restrictions, however, need to be considered in reality.

[0053]

First, there is a limit on the range of the incident angle at which specular resonance occurs with the bisphere's axis, and generally, $|\delta - \alpha| \leq 30°$ approximately holds. In addition, it is preferable that only a single diffracted light be enhanced for high efficiency diffraction. If a plurality of diffracted lights are enhanced, the energy distributed per single diffracted light will decrease. If it is assumed that incident angle $\alpha = 0$ and diffraction order $m = 1$ for simplicity, the angle gap Θ between the transmitted light ($m = 0$) and the diffracted light is $\Theta = \sin^{-1}(\lambda/p)$. Where the angular width (full width at half maximum) of the specular resonance light from a bisphere is denoted as Δθ, several diffracted lights are enhanced simultaneously when $\Delta\theta > \Theta$. Let us assume that the criterion for enhancing only one diffracted light is $\Delta\theta \leq \Theta/2$.

[0054]

Fig. 2 illustrates the range that satisfies this condition. Δθ in Fig. 2 was obtained by averaging the angle width of the specular resonance peak for various incident angle α values with bispheres having various sphere sizes D (size parameter S is expressed normalized by $S = \pi D/\lambda$) and refractive indices n. Fig. 2 shows the fitting curve of Δθ for refractive index $n = 1.58$ (average

for both polarizations). The ranges of distribution of $\Delta\theta$ values for various refractive indices n (1.3 to 2.1) at several size parameter S values also are expressed with bars, which are roughly distributed around the fitting curve.

[0055]

Fig. 2 also shows $\Theta/2$. The solid line represents the case of bilayer close-packed crystal of the present invention, which is being discussed now, and the dashed line will be discussed later. The vertical line (solid line) near size parameter S = 4 represents the diffraction limit, and with size parameter S values less than that, Θ does not exist. In other words, diffraction takes place no longer. In addition, the lower limit of the range in which specular resonance occurs is about size parameter S = 5.

[0056]

From the foregoing, it will be appreciated that the range of S that fulfills the criterion $\Delta\theta \leq \Theta/2$ and in which specular resonance occurs is a very narrow range in the vicinity of size parameter S = 5. This criterion $\Delta\theta \leq \Theta/2$ is not absolute but may be defined arbitrarily according to the required diffraction properties. Generally, the range of size parameter S = about 5 to about 10 is considered the range in which particularly useful diffraction gratings exist with which one diffracted light is enhanced selectively. This range corresponds to D = 0.8 to 1.6 μm for visible light with wavelength $\lambda = 0.5$ μm, and sphere diameter D = 2.5 to 5 μm for an optical communication wavelength of $\lambda = 1.55$ μm.

[0057]

We have confirmed through an experiment that specular-resonance-enhanced diffraction actually occurred and high diffraction efficiency comparable to conventional diffraction gratings resulted.

[0058]

Polymer microspheres (light scatterers) with sphere diameter D = 2.1 μm and refractive index n = 1.58 were stacked as illustrated in Fig. 3 by a micromanipulation method. Reference numeral 21 denotes polymer

microspheres of a first layer, reference numeral 22 denotes a close-packed crystal of the first layer having the polymer microspheres 21 arrayed therein, reference numeral 23 denotes polymer microspheres of a second layer, and reference numeral 24 denotes a close-packed crystal of the second layer having the polymer microspheres 23 arrayed therein.

[0059]

Here, the intensity profile in the xz plane obtained when light with wavelength $\lambda = 0.633$ μm (corresponding to size parameter $S = 10.4$) is incident within the xz plane at various angles α is considered. Fig. 4 illustrates theoretical projections. Fig. 4 is a graph illustrating the intensity profile in the xz plane according to the diffraction theory taking specular resonance of the present invention into account as a structure factor, wherein Fig.4 (a) is a diffraction function taking into account the finiteness of the lattices used in an experiment, Fig.4 (b) is a structure factor representing specular resonance, and Fig.4 (c) is intensity profile at various incident angles α.

[0060]

Fig. 4(a) is an intensity profile taking into account the diffraction that occurs when a finite number of scatterers are arrayed with period p. Here, the horizontal axis represents the Δkx that is the x component of scattering vector $\Delta k = k_o - k_1$. In this notation, the direction in which diffracted light occurs is fixed at a certain position on the horizontal axis and not dependent on the incident angle, and the diffracted light (transmitted light) with diffraction order $m = 0$ always sits at the center at all times. The effect of specular resonance from the bisphere is added thereto. Since specular resonance is the distribution of scattering intensities from individual scatterers, it can be treated as a structure factor in the diffraction theory.

[0061]

From Fig. 2, it will be derived that $\Delta\theta = 15°$ with the just-mentioned size parameter S and refractive index n, the structure factor can be

approximated as a Gaussian distribution with that half-width. Fig. 4(b) shows the result. This peak moves leftward or rightward according to incident angle α. Multiplying Fig. 4(a) and Fig. 4(b) yields the definitive intensity profile of Fig. 4(c). It will be appreciated that diffracted lights with various orders are enhanced selectively one after another as the incident angle α is varied. It can be explained that even though the diffraction grating originally is the one that causes a number of diffracted lights with various orders at the same time as shown by Fig. 4(a), the profile shown by Fig. 4(c) results because it has the blazing effect shown by Fig. 4(b).

[0062]

Fig. 5 illustrates the results of actual measurement of the foregoing. Since the size of the crystal within the plane is limited in the experiment and thus the transmitted light for the peripheral margin portions overlap, the peak for diffraction order m = 0 cannot be compared with that of Fig. 4(c). Nevertheless, the rest of the portions are in good agreement, which demonstrates that the specular-resonance-enhanced diffraction occurred as expected.

[0063]

Two peaks with similar intensities may appear at the same time for some incident angles α, but this is because the size parameter S is set at a relatively large value, slightly exceeding 10. At this time, the diffraction efficiency was greatest under the condition indicated by the circle in Fig. 5, 55% for p polarization and 52% for s polarization. Considering that conventional blazed transmission diffraction gratings typically show diffraction efficiencies of 50 to 80%, almost the same degree of efficiency already has been attained. Moreover, excellent characteristics as a diffraction grating already have been provided in that the difference in diffraction efficiency that is dependent on polarization is small. Here, no optimization was conducted for the arrayed structure used in the experiment. Therefore, if sphere diameter D and refractive index n are selected

appropriately according to the used wavelength λ based on calculations and systematic experimental results, even higher diffraction efficiency will be obtained.

[0064]

Although a close-packed crystal, which is easily fabricated using self-assembly techniques, has been chosen as the subject in the description hereinabove, specular-resonance-enhanced diffraction may occur similarly with other structures.

[0065]

Fig. 6 shows the case where microspheres are arrayed in the form of a tetragonal lattice. Fig. 6 (a) is a plan view of the tetragonal lattice in which the microspheres of the second layer of the tetragonal lattice were partially removed. Fig. 6 (b) is a front view of Fig. 6 (a).

[0066]

In these figures, reference numeral 30 denotes a diffraction grating, reference numeral 31 denotes a transparent substrate, reference numeral 32 denotes microspheres (light scatterers) of a first layer, reference numeral 33 denotes a close-packed crystal of the first layer having the microspheres 32 arrayed therein, reference numeral 34 denotes microspheres (light scatterers) of a second layer, and reference numeral 35 denotes a close-packed crystal of the second layer having the microspheres 34 arrayed therein.

[0067]

In this case as well, the crystals should be disposed in such orientations that bispheres are positioned within the xz plane when light is incident on the xz plane. At this time, inclination angle δ = 450 and period p = 0.707D (D is the diameter of the sphere). The dashed line in Fig. 2 represents Θ/2 and the diffraction limit in this case. It will be appreciated that the tetragonal lattice has a slightly wider range that satisfies the condition in which only a single diffracted light is enhanced. It is difficult to form a tetragonal lattice on the smooth transparent substrate 31 by

self-assembling because the tetragonal lattice is not close-packed in a plane, but if recesses in which the lower portions of the microspheres 32 of the first layer fit are processed in the surface of the transparent substrate 31, it can be fabricated by self-assembling. Nonpatent Document 5 describes this technique.

[0068]

Fig. 7 shows a bilayer crystal obtained by closely packing cylinders (light scatterers) having a sufficient length compared with the diameter thereof. Fig. 7 (a) is a plan view illustrating the bilayer crystal a part of which was removed. Fig. 7 (b) is a front view of Fig. 7 (a).

[0069]

In these figures, reference numeral 40 denotes a diffraction grating, reference numeral 41 denotes a transparent substrate, reference numeral 42 denotes cylinders (light scatterers) of a first layer, reference numeral 43 denotes a close-packed crystal of the first layer having the cylinders 42 arrayed therein, reference numeral 44 denotes cylinders (light scatterers) of a second layer, and reference numeral 45 denotes a close-packed crystal of the second layer having the cylinders 44 arrayed therein. At this time, inclination angle $\delta = 30°$ and period p = sphere diameter D.

[0070]

The diffraction gratings of the examples shown in Fig. 1 and Fig. 6 differ from the diffraction grating with the general conventional one-dimensional periodic structure shown in Fig. 15 also in that it is a two-dimensional diffraction grating, besides in that it employs specular resonance as the blazing principle. The example shown in Fig. 7 is an example in which the conventional one-dimensional diffraction grating is inherited as it is to one with a method using specular resonance. In this example, each layer is formed by merely arraying cylinders in a close-packed manner, allowing the diffraction grating to be fabricated more easily.

[0071]

All the examples described here are ones in which spheres or cylinders are stacked on a substrate while they are in close contact with one another. Nonpatent Document 4, however, describes that it is possible to remove the substrate and retain the structure with the array structure of spheres or cylinders in a self-standing manner. Accordingly, such a system without a substrate may be used as it is. The diffraction conditions and specular resonance conditions are determined by wave vector components in the xy plane, and the xy components of wave vectors are preserved irrespective of the presence or absence of a substrate; therefore, the absence of the substrate makes no particular difference in operating conditions.

[0072]

The foregoing has described a detailed structure and how to determine appropriate values of diameter D and period p by three typical examples. It is desirable that the period with which the light scatterers are arrayed in each of the above-mentioned layers is in a range of 1/2 times to 100 times with respect to the wavelength of the incident light in the medium surrounding the diffraction grating.

[Example 2]

[0073]

Fig. 8 is a view illustrating a diffraction grating according to the present invention in which two substrates are fixed facing each other. A monolayer close-packed crystal of microspheres is formed on each of the substrates.

[0074]

In this figure, reference numeral 50 denotes a diffraction grating, reference numeral 51 denotes a first transparent substrate, reference numeral 52 denotes first spheres (light scatterers) on the first transparent substrate, reference numeral 53 denotes a monolayer close-packed crystal having the spheres 52 arrayed therein, reference numeral 54 denotes a second transparent substrate, reference numeral 55 denotes second spheres (light

scatterers) on the second transparent substrate, reference numeral 56 denotes a monolayer close-packed crystal having the spheres 55 arrayed therein, reference numeral 57 denotes silica spheres (or glass micro rods), and reference numeral 58 denotes adhesive.

[0075]

In this example, the first transparent substrate 51 on which the monolayer close-packed crystal 53 of the first spheres 52 are formed and the second transparent substrate 54 on which the monolayer close-packed crystal 56 of the second spheres 55 are formed are fixed facing each other with an appropriate space therebetween. Although the diffraction gratings in which the first layer and the second layer are in close contact with each other as shown in Fig. 1, Fig. 6 and Fig. 7 can be fabricated easily, the inclination angle δ of the bisphere units in the xz plane cannot be selected arbitrarily. The diffraction grating illustrated in Fig. 8 is an improved version in this respect and can realize arbitrary inclination angle δ by the position matching in a plane. When each crystal face has a structure of triangular lattice, it can be fabricated in a self-assembled manner as described in Nonpatent Document 4. Even when each crystal face has a structure of other lattices, it can be realized with ease in combination with the method described in Nonpatent Document 5.

[0076]

What should be noted when fabricating the diffraction grating shown in Fig. 8 is to precisely control the space between the two transparent substrates 51 and 54, and this can be realized because the techniques of securing two flat surfaces at a small gap on the order of micrometers already have been in commercial use for liquid crystal displays and stacked diffraction grating optical elements for camera lenses. Specifically, it can be realized by mixing the silica spheres 57 with a uniform particle size or glass micro rods as spacers in peripheral adhesive portions, or forming protrusions serving as spacers in peripheral portions by a molding process so as to put and adhere

onto the substrates facing each other. Fig. 8 illustrates a method for using the silica spheres 57 as spacers.

[Example 3]

[0077]

Fig. 9 is a view illustrating a diffraction grating configured so that two substrates with a monolayer close-packed crystal of cylinders formed thereon are placed facing each other and the upper layer and the lower layer are allowed to shift relatively by a driving device.

[0078]

In this figure, reference numeral 60 denotes a diffraction grating, reference numeral 61 denotes a first substrate, reference numeral 62 denotes cylinders (light scatterers) on the first substrate, reference numeral 63 denotes a monolayer close-packed crystal having the cylinders 62 arrayed therein, reference numeral 64 denotes a second substrate, reference numeral 65 denotes cylinders (light scatterers) on the second substrate, reference numeral 66 denotes a monolayer close-packed crystal having the cylinders 65 arrayed therein, reference numeral 67 denotes a driving device (a piezoelectric element or an electrostatic actuator), reference numeral 68 denotes incident light, and reference numeral 69 denotes diffracted light.

[0079]

The case where the cylinders 62 and 65 are one-dimensionally arrayed respectively is described here for simplicity,, but the same applies to a two-dimensional array of triangular lattice of spheres or a two-dimensional array of tetragonal lattice of spheres as described above.

[0080]

Example 3 is similar to Example 2, but is different in that the upper and lower layers (the cylinders 62 and 65) can shift relatively by the driving device 67. Specifically, it is possible to use a piezoelectric element and an electrostatic actuator fabricated by a semiconductor process technique called MEMS (microelectro-mechanical system) as the driving device 67.

Hereinbelow, the functions that can be realized by the relative shifting of the layers (the cylinders 62 and 65) will be mainly discussed.

[0081]

The first function is dynamic switching for the order of diffracted light to be enhanced. Assuming incident angle $\alpha = 0$ for simplicity, the direction in which the diffracted light 69 with order m occurs is represented as $\theta_m = \sin^{-1}(m\lambda/p)$. When the upper layer (the cylinders 65) is shifted by Δx with respect to the lower layer (the cylinders 62), the angle that bispheres form with respect to the incident light is $\delta = \tan^{-1}(\Delta x/(D + G))$, where G represents the distance between the cylinder surfaces between the layers. When Δx exceeds period p, the same situation is repeated, so $|\Delta x| \leq p/2$. When Δx is selected so that $\theta_m = 2\delta$, it will be possible to enhance diffracted light with a specific order m.

[0082]

Here, when it is assumed that $D \gg G$, $\theta_m \fallingdotseq \sin\theta_m$, $\delta \fallingdotseq \tan\delta$, and $D \fallingdotseq p$, Δx that enables the m-order light to be enhanced can be expressed as $\Delta x \fallingdotseq m\lambda/2$. When it is thought that wavelength $\lambda = 500$ nm and diffraction order $m = \pm 1$, the range of Δx is ± 250 nm. Approximately the same range will result from the condition $|\Delta x| \leq p/2$. This means that by merely shifting the upper layer 66 and lower layer 63 in a range of ± 250 nm, it becomes possible to enhance selectively only one of the diffracted lights that proceed in three directions $m = -1$, 0, and +1. The shifting to this degree is easy even with a piezoelectric element or an MEMS actuator.

[0083]

The second function is a function to satisfy the blazing condition and guarantee high efficiency diffraction constantly for various wavelengths λ.

[0084]

Fig. 10 is a view illustrating spectral measurements being performed by the diffraction grating shown in Fig. 9

[0085]

In this figure, reference numeral 70 denotes a slit and reference numeral 71 denotes a light detection device.

[0086]

An example is considered in which the white incident light 68 is decomposed spectrally with the diffraction grating 60 and the light with a specified wavelength λ is taken out by letting it through the slit 70 to measure the intensity thereof. Selecting of wavelength λ can be effected by, for example, rotating the diffraction grating 60 with respect to the incident light 68 (that is, changing incident angle α).

[0087]

Assuming that the slit 70 is fixed in the direction of β from the incident direction of light, $\theta - \alpha = \beta$ as can be understood from Fig. 10. From the grating equation, incident angle α should be chosen so that $\sin(\alpha + \beta) - \sin\alpha = m\lambda/p$ at this time.

[0088]

In order to satisfy the specular resonance condition at the same time, $\delta = \alpha + \beta/2$ needs to be satisfied. In other words, by determining incident angle α, inclination angle δ is also determined, and if Δx is adjusted to be so, it will mean that blazing is always carried out for the wavelength λ that is to be measured. As already described, since conventional diffraction gratings have been unable to change the blazing condition dynamically in this way, they have satisfied the blazing condition only at a typical wavelength used and a compromise always has been made with other wavelengths at a lower efficiency.

[0089]

Considering that the driving as described above is performed with an MEMS actuator, the use of a self-assembled array of spheres or cylinders for the diffraction grating is not very realistic. This is because since an advantage of MEMS is that it can realize a fine structure of complicated shape with high precision and at relatively low cost through collective forming using

semiconductor process technique, the original advantage of adopting MEMS will be spoiled if the processes of combining many discrete parts, such as spheres and cylinders, are included.

[0090]

As indicated in the above-mentioned Nonpatent Document 3, in specular resonance, the spheres or cylinders on the incident side serve as a focusing lens for focusing the incident collimated light while the spheres or cylinders on the emission side serve as a collimating lens for putting the light back into collimated light. A single layer array of spheres or cylinders may be replaced with a sphere or cylinder type, or a graded-refractive-index type microlens array (a crystal of microlenses) equivalent to them.

[0091]

The shape and the refractive index distribution of unit scatterer that yield the utmost efficiency for the diffraction grating of the present invention should be obtained by rigorous calculations of Maxwell's equations. In that case, light scatterers will be aspherical or non-cylindrical lenses, or equivalent graded-refractive-index type lenses. The sphere or cylinder array described in the above-mentioned examples should be considered rather as a special example that is easily fabricated while the performance is compromised somewhat. A microlens array itself is a typical MEMS, and much research has been conducted on the method for realizing the microlens array making full use of lithography and etching techniques. It is expected that the integration of microlens array and its driving mechanism makes it possible to produce the diffraction gratings according to the invention with an optimum shape and in high volume.

[0092]

Fig. 11 is an example in which the configuration of Fig. 9 is realized by microlens arrays.

[0093]

In this figure, reference numeral 80 denotes a diffraction grating,

reference numeral 81 denotes a first substrate, reference numeral 82 denotes microlenses (light scatterers) on the first substrate, reference numeral 83 denotes a microlens array having microlenses 82 arrayed therein, reference numeral 84 denotes a second substrate, reference numeral 85 denotes microlenses on the second substrate, reference numeral 86 denotes a microlens array having the microlenses 85 arrayed therein, and reference numeral 87 denotes a driving device (a piezoelectric element or an electrostatic actuator).

[0094]

Here, the focal distance of microlenses 82 and that of microlenses 85 are shown to be equal, but they may be different. In that case, although specular resonance light goes out in a specific direction determined by the ratio of the focal distance and the incident direction, the basic idea is the same as having described above. As in the case where spheres or cylinders are used as light scatterers, it is desirable that the period with which the light scatterers are arrayed in each of the above-mentioned layers is in a range of 1/2 times to 100 times with respect to the wavelength of the incident light in the medium surrounding the diffraction grating.

[0095]

In Fig. 9, the direction of the driving is illustrated only for the x-axis direction, but the direction of the driving of the present invention is not limited to one axial direction like this. In the case of two-dimensional arrays of spheres or lenses, diffracted light in another direction also can be enhanced by shifting also in the y-axis direction. In addition, if the driving in the z-axis direction is possible, the greatest diffraction efficiency always can be attained by optimization of the distance between the two layers.

[0096]

Considering the applications of diffraction gratings to date, it is expected that the diffraction grating according to the present invention described above will find similar ways of application.

[0097]

Fig. 12 is a first application example in which the diffraction grating is applied to a so-called grism.

[0098]

In this figure, reference numeral 90 denotes a grism, reference numeral 91 denotes a prism, and reference numeral 92 denotes a diffraction grating. The diffraction grating 92 includes cylinders (light scatterers) of a first layer 93, a close-packed crystal of the first layer 94 having the cylinders 93 arrayed therein, cylinders (light scatterers) of a second layer 95, and a close-packed crystal of the second layer 96 having the cylinders 95 arrayed therein. Reference numeral 97 denotes incident light and reference numeral 98 denotes diffracted light.

[0099]

The grism is a hybrid optical component of the diffraction grating (grating) 92 and the prism 91, in which required diffracted light (m = 1) is adjusted to be coaxial with the incident light 97 due to the polarization effect of the prism 91.

[0100]

By combining the diffraction grating 92 with the prism 91 as shown in Fig. 12, it similarly becomes possible to take out a predetermined wavelength by merely inserting it into an optical system so that, for example, the image can be observed as it is. The following examples of applications all illustrate a one-dimensional array of cylinders 93 and 95. Needless to say, however, each can be replaced with other developments such as the above-mentioned Example 2 and 3.

[0101]

Fig. 13 is a second example of application in which the diffraction grating according to the present invention is applied to a grating coupler for an optical waveguide.

[0102]

In this figure, reference numeral 101 denotes a substrate, reference numeral 102 denotes an optical waveguide, and reference numeral 103 denotes a diffraction grating. The diffraction grating 103 includes cylinders (light scatterers) of a first layer 104, a close-packed crystal 105 of the first layer having the cylinders 104 arrayed therein, cylinders (light scatterers) of a second layer 106, and a close-packed crystal 107 of the second layer having the cylinders 106 arrayed therein. Reference numeral 108 and 109 denote incident lights and reference numeral 110 and 111 denote diffracted lights.

[0103]

When recesses for positioning spheres or cylinders are processed in a location where a coupler is to be formed, it is possible to incorporate the diffraction grating 103 at a predetermined location in a self-assembled manner.

[0104]

Since the diffraction grating 103 according to the present invention is equivalent to the one that is blazed, light does not propagate in both directions and the diffracted lights 110 and 111 can be guided or taken out only in a specific direction from the coupler.

[0105]

Fig. 14 is a third example of application in which the diffraction grating of the present invention is used for an encoder for position detecting.

[0106]

In this figure, reference numeral 121 denotes a first structure, reference numeral 122 denotes a transparent substrate, reference numeral 123 denotes microlenses, reference numeral 124 denotes a microlens array having the microlenses arrayed therein, reference numeral 125 denotes a second structure, reference numeral 126 denotes a transparent substrate, reference numeral 127 denotes microlenses, and reference numeral 128 denotes a microlens array having the microlenses arrayed therein. Here, scales are configured by having the microlens arrays on the transparent

substrates. Reference numeral 130 denotes incident light, reference numerals 131 to 135 denote diffracted lights, and reference numerals 141 to 145 denote a first to fifth light detection devices. The graph on the right-hand side of Fig. 14 shows output waveforms from the first to fifth light detection devices 141 to 145.

[0107]

As shown in Fig. 9, the relative shifting of the two layers of the diffraction grating by only a very small distance of several hundred nanometers changes which order of diffracted light is enhanced. This is utilized for position detecting. Two scales, each of which is formed with the microlens array disposed on the transparent substrate, are attached to the two structures 121 and 125 respectively so as to face each other. The two structures 121 and 125 relatively move. When the incident light 130 is incident thereon, the diffracted lights 131 to 135 with a plurality of orders are produced. The light detection devices 141 to 145 are provided in the respective directions of the diffracted lights 131 to 135 for detecting the signal intensities for the respective orders (Fig. 14 illustrates an example in which the intensities of five diffracted lights up to ±2 orders are detected). When the two structures 121 and 125 move relatively, the diffraction order that is enhanced changes one after another, and the detection device detecting a strong signal changes accordingly one after another. When the quantity of relative motion becomes equal to the period p of the diffraction grating, the device goes back to the initial state.

[0108]

Thus, a change in position can be measured with a resolution of about several hundred nanometers. If signals are interpolated as with a conventional encoder, it is possible to measure the position with a still finer resolution. Patent Document 1 describes a similar method of position matching with two diffraction gratings combined. This method uses a lens effect of a diffraction optical element that serves as one Fresnel lens as a

whole. In contrast, in the present invention, each scattering element itself serves as a lens. So the entire configuration rather provides no lens effect and is completely different theoretically. Moreover, as an embodiment, it is important in the present invention to make the two layers of the diffraction grating adjacent to each other. And the present invention is largely different in that a pair of the layers serves as one blazed diffraction grating as a whole. In addition, Patent Document 2 utilizes a resonant diffraction effect of a periodic structure similarly formed of spheres. What is utilized there, however, is a synergistic effect of Me resonance and Bragg diffraction conditions. Whereas, the phenomenon that the present invention utilizes is rather a geometrical optical phenomenon unrelated to Mie resonance as described in the above-mentioned Nonpatent Document 3. The present invention is different in that it is peculiar to a bilayer crystal. The incident condition under which unique diffraction is observed also is different. In the present invention, it is necessary for the bispheres to be parallel to a plane including incident light and diffracted light.

[0109]

While particular embodiments of the invention have been described above, the invention may be practiced in various other forms without departing from the spirit thereof. For example, although the light diffraction phenomenon has been discussed as a main theme herein, the same principle holds for electromagnetic waves in general, such as microwaves and millimeter waves because the phenomena that can be expressed by Maxwell's equations are dealt with here. Although all the examples described hereinabove employed transmission diffraction gratings, there is no particular reason that the transmission type must be used, and the present invention also includes a diffraction grating that is combined with a mirror to form a reflective type diffraction grating. Furthermore, as conventionally performed with conventional optical elements, providing an anti-reflection coating or the like on a surface of the diffraction grating of the present

invention is merely one example of the present invention. The substrates illustrated in the examples are described for simplicity with an assumption that they have flat surfaces, but the same effect will be obtained even in cases where monolayer close-packed crystals are formed on two curved substrates.

[0110]

Consequently, the present invention is not limited to the above-mentioned examples. Various modifications can be made based on the intention of the present invention and will not be excluded from the scope of the present invention.

[Industrial Applicability]

[0111]

The diffraction grating of the present invention and the device using the diffraction grating are suitable for low-cost or tunable optical spectroscopes, optical integrated circuits, and position detecting devices.

[Brief Description of the Drawings]

[112]

[Fig. 1] Fig. 1 is a view for describing specular-resonance-enhanced diffraction by a bilayer close-packed crystal of transparent microspheres according to the present invention.

[Fig. 2] Fig. 2 is a graph illustrating the conditions under which only a single diffracted light is enhanced by the specular resonance according to the present invention.

[Fig. 3] Fig. 3 is a view illustrating an array of polymer microspheres with a diameter of 2.1 μm and a refractive index of 1.58 that were used for the experiments according to the present invention.

[Fig. 4] Fig. 4 is a graph illustrating an intensity profile in the xz plane according to the diffraction theory taking the specular resonance of the present invention into account as a structure factor.

[Fig. 5] Fig. 5 is a graph illustrating an intensity profile in the xz plane obtained by experiments according to the present invention.

[Fig. 6] Fig. 6 is a view illustrating a bilayer crystal according to the present invention having the microspheres arrayed in the form of a tetragonal lattice.

[Fig. 7] Fig. 7 is a view illustrating a bilayer close-packed crystal of cylinders according to the present invention.

[Fig. 8] Fig. 8 is a view illustrating a diffraction grating according to the present invention in which two substrates are fixed facing each other and a monolayer close-packed crystal of microspheres is formed on each of the substrates.

[Fig. 9] Fig. 9 is a view illustrating a diffraction grating according to the present invention configured so that two substrates with a monolayer close-packed crystal of cylinders formed thereon are placed facing each other and the upper and lower layers are allowed to shift relatively by a driving device.

[Fig. 10] Fig. 10 is a view illustrating light detection being performed by the diffraction grating shown in Fig. 9.

[Fig. 11] Fig. 11 is a view illustrating an example in which the configuration of Fig. 9 is realized by microlens arrays.

[Fig. 12] Fig. 12 is a view illustrating an example in which the diffraction grating according to the present invention is applied to a grism.

[Fig. 13] Fig. 13 is a view illustrating an example in which the diffraction grating according to the present invention is applied to a grating coupler for an optical waveguide.

[Fig. 14] Fig. 14 is a view illustrating an example in which the diffraction grating of the present invention is applied to an encoder for position detecting.

[Fig. 15] Fig. 15 is a schematic view of a conventional blazed diffraction grating.

[Explanation of Numerals]

[113]

10, 30, 40, 50, 60, 80, 103 Diffraction grating

11, 31, 41, 122, 126 Transparent substrate

12, 32 Transparent microspheres (light scatterers) of the first layer

13, 22, 33, 43, 94, 105 Close-packed crystal of the first layer

14, 34 Microspheres (light scatterers) of the second layer

15, 24, 35, 45, 96, 107 Close-packed crystal of the second layer

21 Polymer microspheres of the first layer

23 Polymer microspheres of the second layer

42, 93, 104 Cylinders (light scatterers) of the first layer

44, 95, 106 Cylinders (light scatterers) of the second layer

51 First transparent substrate

52 First spheres (light scatterers)

53, 56, 63, 66 Monolayer close-packed crystal

54 Second transparent substrate

55 Second spheres (light scatterers)

57 Silica spheres

58 Adhesive

61, 81 First substrate

62, 65 Cylinders (light scatterers)

64, 84 Second substrate

67, 87 Driving device (piezoelectric element or electrostatic actuator)

68, 97, 108, 109, 130 Incident light

69, 98, 110, 111, 131 to 135 Diffracted light

70 Slit

71, 141 to 145 Light detection device

82, 85, 123, 127 Microlenses (light scatterers)

83, 86, 124, 128 Microlens array

90 Grism

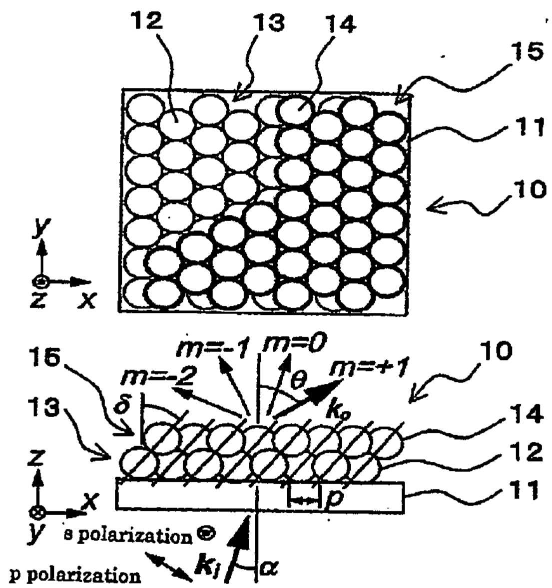
91 Prism

92 Diffraction grating

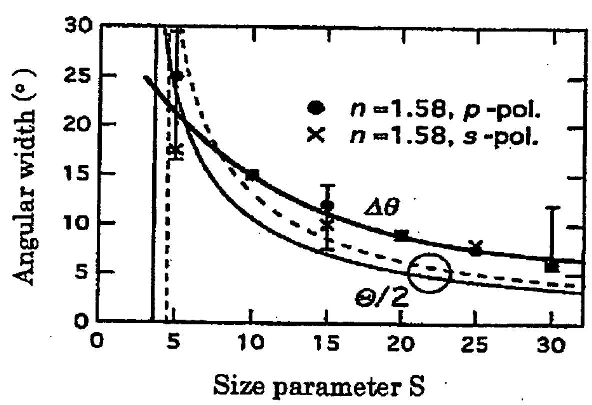
101	Substrate
102	Optical waveguide
121	First structure
125	Second structure

[Document Name] Drawings

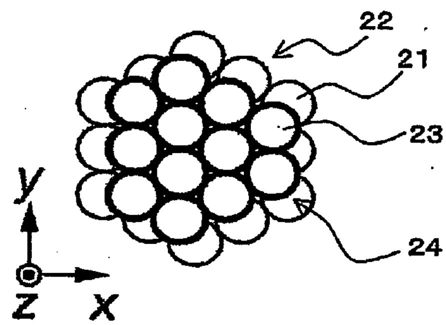
[Fig. 1]



[Fig. 2]



[Fig. 3]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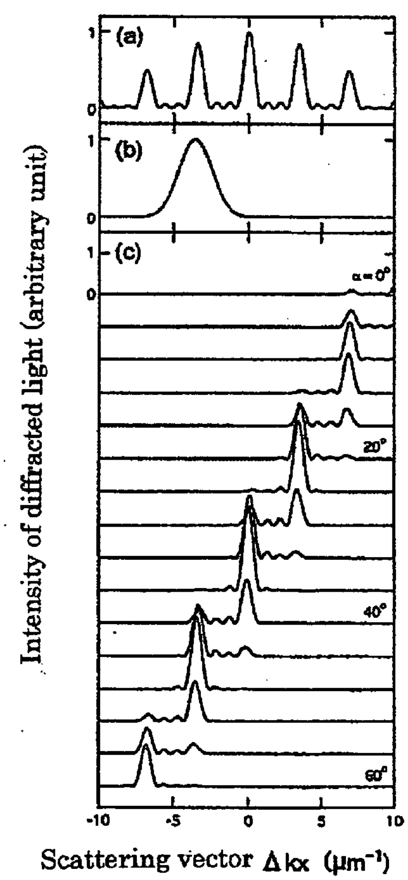
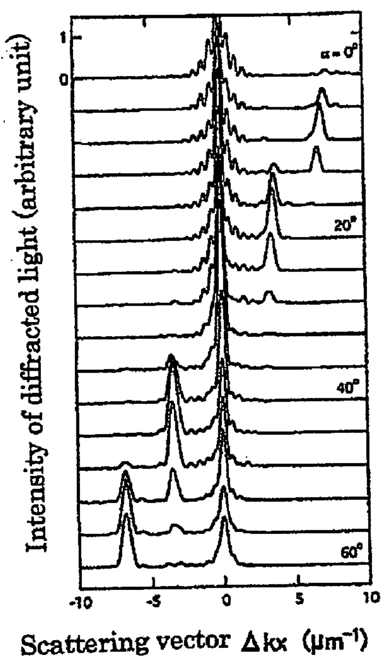
21
23
24
y
Z
X

[Fig. 4]


Intensity of diffracted light (arbitrary unit)
(a)
(b)
(c)
1
0
α=0°
20°
40°
60°
-10
-5
0
5
10
Scattering vector Δkx (μm⁻¹)

[Fig. 5]


Intensity of diffracted light (arbitrary unit)
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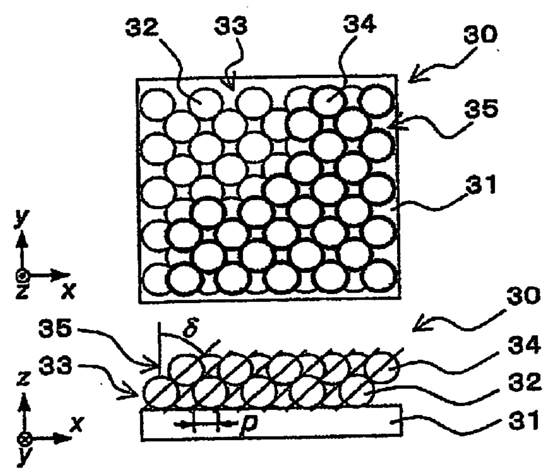
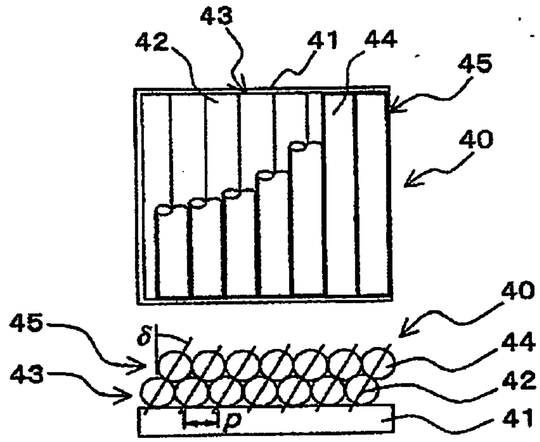
0
α = 0°
20°
40°
60°
-10
-5
0
5
10
Scattering vector Δkx (μm⁻¹)

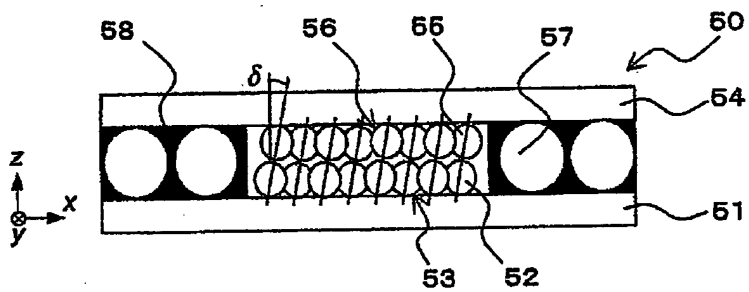
[Fig. 6]


32
33
34
30
35
31
y
z
x
30
35
δ
34
33
32
z
x
p
31
y

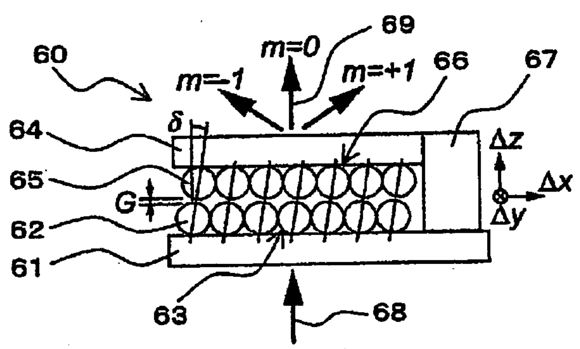
[Fig. 7]



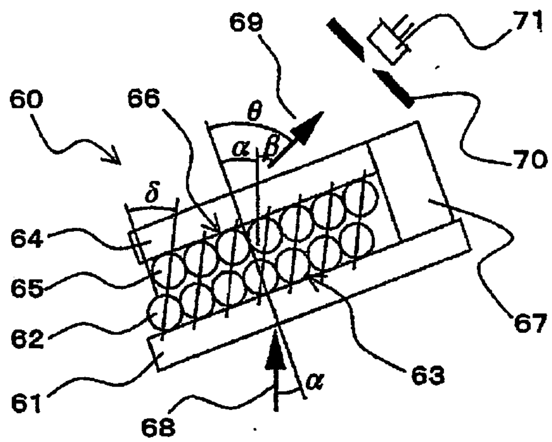
[Fig. 8]



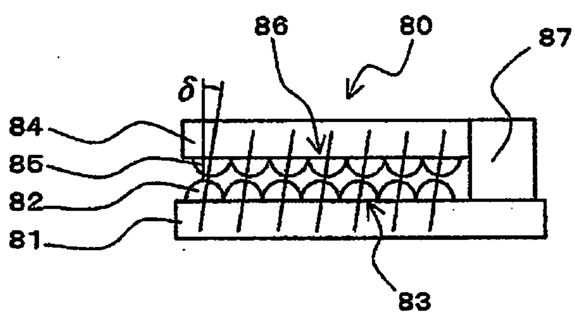
[Fig. 9]



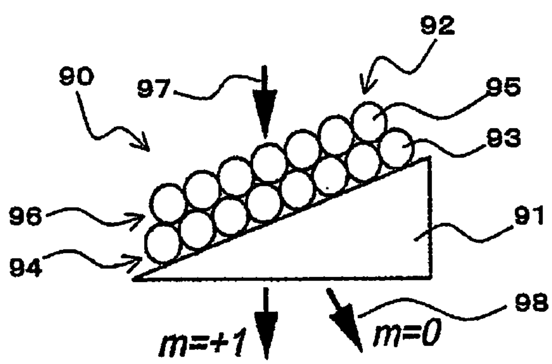
[Fig. 10]



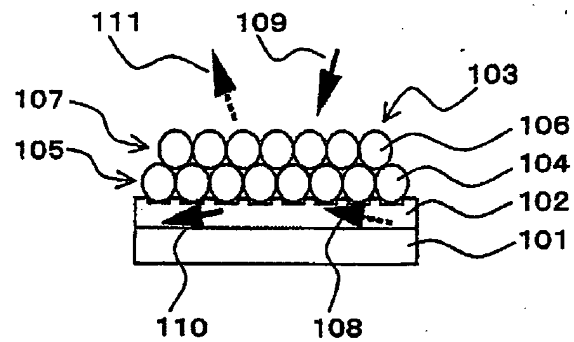
[Fig. 11]



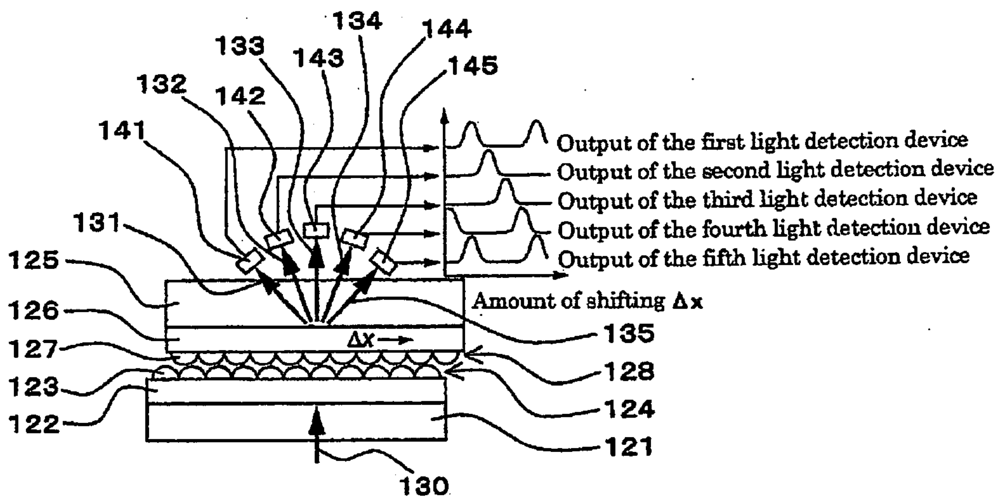
[Fig. 12]



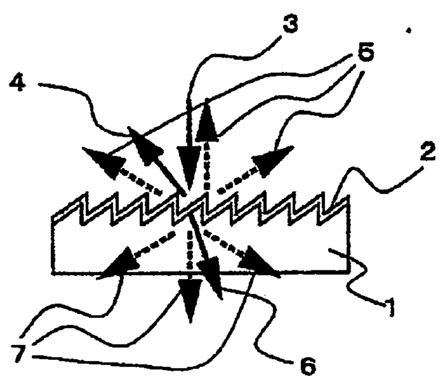
[Fig. 13]



[Fig. 14]



[Fig. 15]



[Document Name] Abstract

[Abstract]

[Object] The present invention provides a diffraction grating that gives novel blazing principle that is simple and effective even in the resonance domain, realizes a high efficiency diffraction grating by a relatively easy fabrication method, and further has tunability that can realize optimum blazing condition according to various use conditions by a control signal from outside. The present invention also provides a device using the diffraction grating.

[Means for Achieving the Object] The diffraction grating includes a first layer (13) having first light scatterers (12) periodically arrayed therein and a second layer (15) having second light scatterers (14) arrayed therein with the same period as that of the first light scatterers (12) in the first layer (13), wherein a direction in which incident light applied from a direction out of planes of the first layer and the second layer is diffracted by these layers is aligned with a direction in which a unit formed of one of the first light scatterers (12) and one of the second light scatterers (14), which are adjacent to each other, scatters the incident light especially intensely so that diffracted light with a single order or a plurality of orders is enhanced selectively.

[Selected Figure] Fig. 1

PATENT COOPERATION TREATY PCT/JP2004/009342

From the INTERNATIONAL BUREAU

PCT

NOTIFICATION OF TRANSMITTAL
OF COPIES OF TRANSLATION
OF THE INTERNATIONAL PRELIMINARY REPORT
ON PATENTABILITY
(CHAPTER I OR CHAPTER II
OF THE PATENT COOPERATION TREATY)

(PCT Rules 44*bis*.3(c) and 72.2)

To:

KAMADA, Koichi
7th Fl., TOMOE MARION BLDG., 4-3-1, Nishitenma,
Kita-ku, Osaka-shi Osaka
5300047
JAPON

Date of mailing *(day/month/year)* 26 May 2006 (26.05.2006)	
Applicant's or agent's file reference FKG04001WO	**IMPORTANT NOTIFICATION**
International application No. PCT/JP2004/009342	International filing date *(day/month/year)* 01 July 2004 (01.07.2004)
Applicant JAPAN SCIENCE AND TECHNOLOGY AGENCY et al	

1. **Transmittal of the translation to the applicant.**

☑ The International Bureau transmits herewith a copy of the English translation of the international preliminary report on patentability (Chapter I).

☐ The International Bureau transmits herewith a copy of the English translation of the international preliminary report on patentability (Chapter II).

2. **Transmittal of the copy of the translation to the designated or elected Offices.**

The International Bureau notifies the applicant that copies of that translation have been transmitted to the following designated or elected Offices requiring such translation:

None

The following designated or elected Offices, having waived the requirement for such a transmittal at this time, will receive copies of that translation from the International Bureau only upon their request:

AE, AG, AL, AM, AP, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EA, EC, EE, EG, EP, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OA, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW

3. **Reminder regarding translation into (one of) the official language(s) of the elected Office(s).**

The applicant is reminded that, where a translation of the international application must be furnished to an elected Office, that translation must contain a translation of any annexes to the international preliminary report on patentability (Chapter II).

It is the applicant's responsibility to prepare and furnish such translation directly to each elected Office concerned within the applicable time limit (Rule 74.1). See Volume II of the PCT Applicant's Guide for further details.

The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland Facsimile No.+41 22 740 14 35	Authorized officer Yoshiko Kuwahara Facsimile No.+41 22 338 90 90

Form PCT/IB/338 (January 2004)

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

(Chapter I of the Patent Cooperation Treaty)

(PCT Rule 44*bis*)

Applicant's or agent's file reference FKG04001WO	**FOR FURTHER ACTION**	See item 4 below
International application No. PCT/JP2004/009342	International filing date *(day/month/year)* 01 July 2004 (01.07.2004)	Priority date *(day/month/year)* 01 July 2003 (01.07.2003)
International Patent Classification (8th edition unless older edition indicated) See relevant information in Form PCT/ISA/237		
Applicant JAPAN SCIENCE AND TECHNOLOGY AGENCY		

1. This international preliminary report on patentability (Chapter I) is issued by the International Bureau on behalf of the International Searching Authority under Rule 44 *bis*.1(a).

2. This REPORT consists of a total of 4 sheets, including this cover sheet.

   In the attached sheets, any reference to the written opinion of the International Searching Authority should be read as a reference to the international preliminary report on patentability (Chapter I) instead.

3. This report contains indications relating to the following items:

   - [x] Box No. I — Basis of the report
   - [ ] Box No. II — Priority
   - [ ] Box No. III — Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   - [ ] Box No. IV — Lack of unity of invention
   - [x] Box No. V — Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
   - [ ] Box No. VI — Certain documents cited
   - [ ] Box No. VII — Certain defects in the international application
   - [ ] Box No. VIII — Certain observations on the international application

4. The International Bureau will communicate this report to designated Offices in accordance with Rules 44*bis*.3(c) and 93*bis*.1 but not, except where the applicant makes an express request under Article 23(2), before the expiration of 30 months from the priority date (Rule 44*bis*.2).

	Date of issuance of this report 15 May 2006 (15.05.2006)
The International Bureau of WIPO 34, chemin des Colombettes 1211 Geneva 20, Switzerland Facsimile No. +41 22 740 14 35	Authorized officer Yoshiko Kuwahara Telephone No. +41 22 338 90 90

Form PCT/IB/373 (January 2004)

PATENT COOPERATION TREATY

TRANSLATION

From the
INTERNATIONAL SEARCHING AUTHORITY

To:

PCT

WRITTEN OPINION OF THE
INTERNATIONAL SEARCHING AUTHORITY

(PCT Rule 43*bis*.1)

		Date of mailing (*day/month/year*)
Applicant's or agent's file reference: FKG04001WO		**FOR FURTHER ACTION** See paragraph 2 below
International application No.: PCT/JP2004/009342	International filing date (*day/month/year*): 01.07.2004	Priority date (*day/month/year*): 01.07.2003
International Patent Classification (IPC) or both national classification and IPC		
Applicant: JAPAN SCIENCE AND TECHNOLOGY AGENCY		

1. This opinion contains indications relating to the following items:

- [x] Box No. I — Basis of the opinion
- [ ] Box No. II — Priority
- [ ] Box No. III — Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
- [ ] Box No. IV — Lack of unity of invention
- [x] Box No. V — Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
- [ ] Box No. VI — Certain documents cited
- [ ] Box No. VII — Certain defects in the international application
- [ ] Box No. VIII — Certain observations on the international application

2. **FURTHER ACTION**

If a demand for international preliminary examination is made, this opinion will be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA") except that this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notified the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of 3 months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

For further options, see Form PCT/ISA/220.

3. For further details, see notes to Form PCT/ISA/220.

Name and mailing address of the ISA/JP	Authorized officer
Facsimile No.	Telephone No.

Form PCT/ISA/237 (cover sheet) (January 2004)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No.
PCT/JP2004/009342

Box No. I **Basis of this opinion**

1. With regard to the language, this opinion has been established on the basis of the international application in the language in which it was filed, unless otherwise indicated under this item.

☐ This opinion has been established on the basis of a translation from the original language into the following language ____________, which is the language of a translation furnished for the purposes of international search (under Rule 12.3 and 23.1(b)).

2. With regard to any nucleotide and/or amino acid sequence disclosed in the international application and necessary to the claimed invention, this opinion has been established on the basis of:

   a. type of material
      ☐ a sequence listing
      ☐ table(s) related to the sequence listing

   b. format of material
      ☐ in written format
      ☐ in computer readable form

   c. time of filing/furnishing
      ☐ contained in the international application as filed.
      ☐ filed together with the international application in computer readable form.
      ☐ furnished subsequently to this Authority for the purposes of search.

3. ☐ In addition, in the case that more than one version or copy of a sequence listing and/or table(s) relating thereto has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

4. Additional comments:

Form PCT/ISA/237 (Box No. I) (January 2004)

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY

International application No. PCT/JP2004/009342

Box No. V Reasoned statement under Rule 43bis.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Claims	1-14	YES
	Claims		NO
Inventive step (IS)	Claims	1-14	YES
	Claims		NO
Industrial applicability (IA)	Claims	1-14	YES
	Claims		NO

2. Citations and explanations:

Document 1: JP 2003-119623 A (Nissan Motor Co., Ltd.), 23 April 2003, Full text; all drawings & US 2003/0031846 A1

Document 2: Hideki T. MIYAZAKI et al., Photonic band in two-dimensional lattices of micrometersized spheres mechanically arranged under a scanning electron microscope, Journal of Applied Physics, 15 May 2000, Vol. 87, No. 10, p. 7152-7158

Document 3: Hideki T. MIYAZAKI et al., Anomalous scattering from dielectric bispheres in the specular direction, Optics Letters, 15 July 2002, Vol. 27, No. 14, pages 1208-1210

The inventions of claims 1-14 cited in the ISR are neither described in any of the documents cited in the ISR nor obvious.